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Mooney et al.

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(54) INTEGRATED CIRCUIT CHIP TEMPERATURE SENSOR

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H03F 3/04 (2006.01)
H03F 1/30 (2006.01)

(52) **U.S. Cl.**
CPC ***H03F 1/30*** (2013.01)
USPC **330/289**; 330/307

(58) **Field of Classification Search**
USPC 330/289, 298, 307; 257/537, 538
See application file for complete search history.

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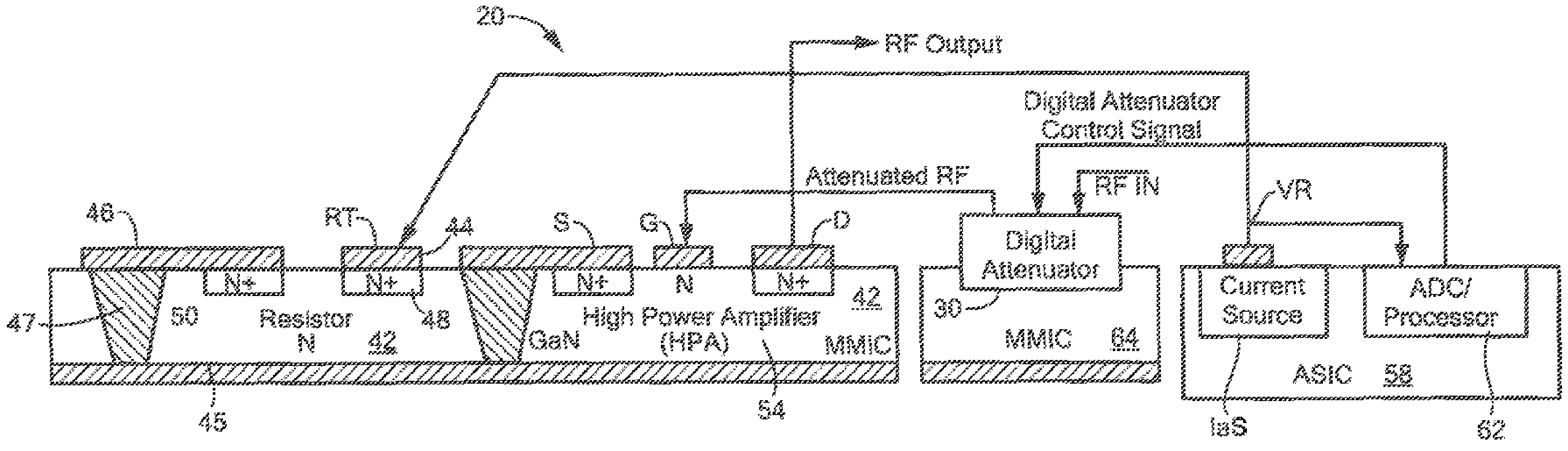
(57) ABSTRACT

A temperature control system having: a resistor formed in a region of a semiconductor, such resistor having a pair of spaced electrodes in ohmic contact with the semiconductor; at least one device formed in another region of the semiconductor thermally proximate the resistor formed region, such device generating heat in the semiconductor; and circuitry, including a reference connected to one of the pair of electrodes, for operating the resistor in saturation and for sensing variation in the resistor in response to the heat generated by the device and for controlling the heat generated by the device in the semiconductor in response to the sensed variation.

20 Claims, 4 Drawing Sheets



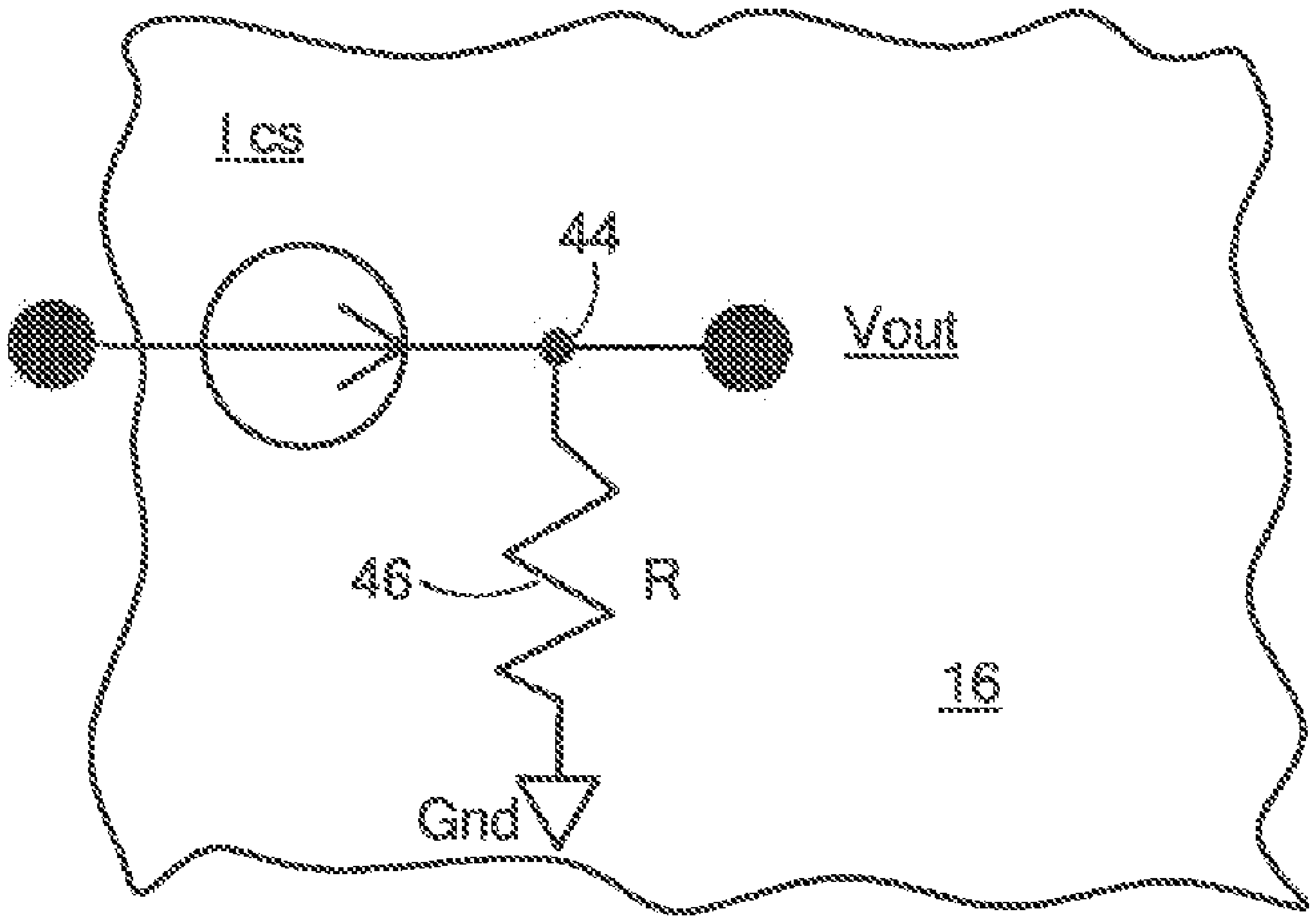

I cs
44
Vout
46
R
16
Gnd

FIG. 1

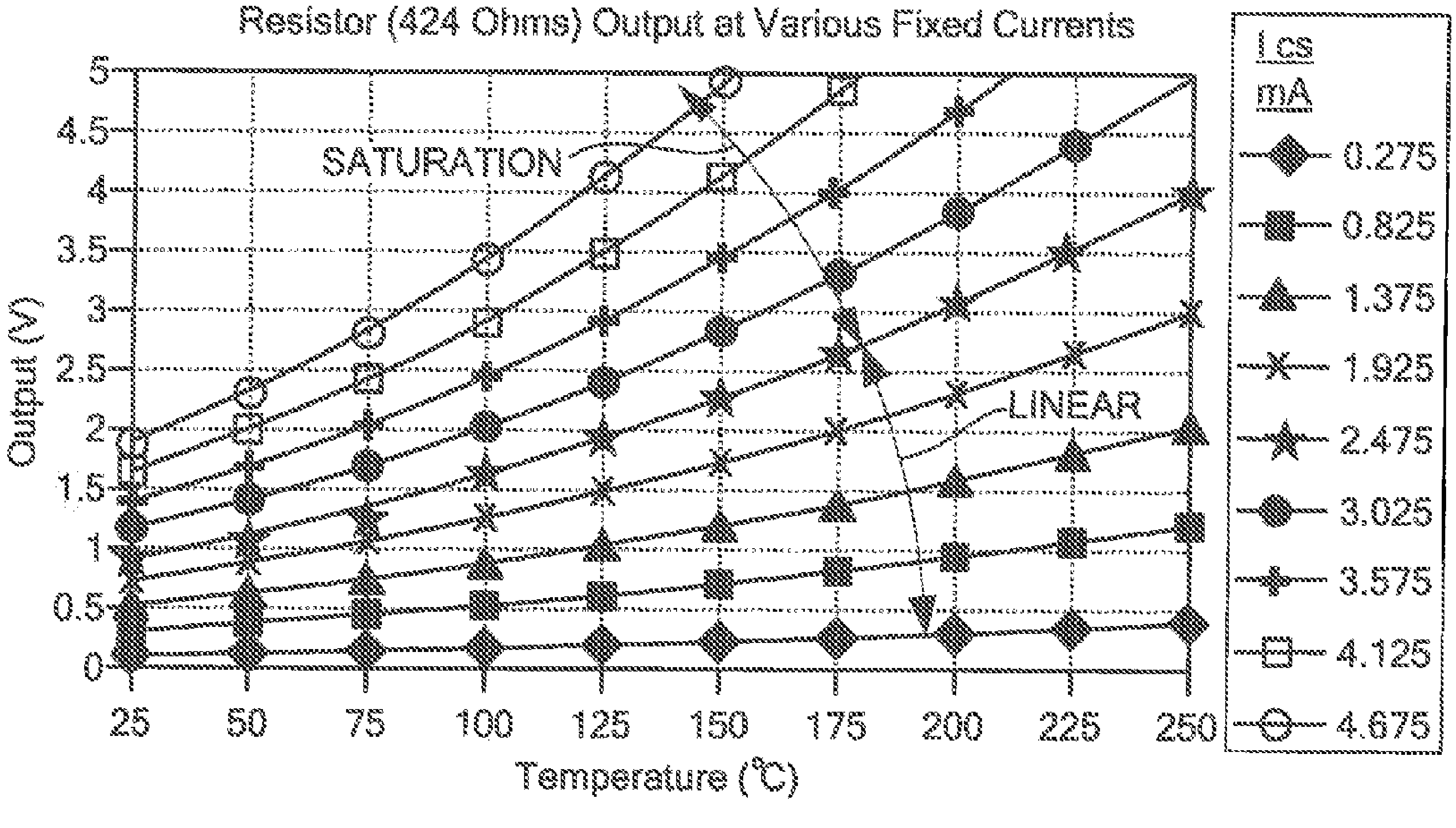

Resistor (424 Ohms) Output at Various Fixed Currents
Output (V)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
25
50
75
100
125
150
175
200
225
250
Temperature (°C)
SATURATION
LINEAR
I cs
mA
0.275
0.825
1.375
1.925
2.475
3.025
3.575
4.125
4.675

FIG. 2

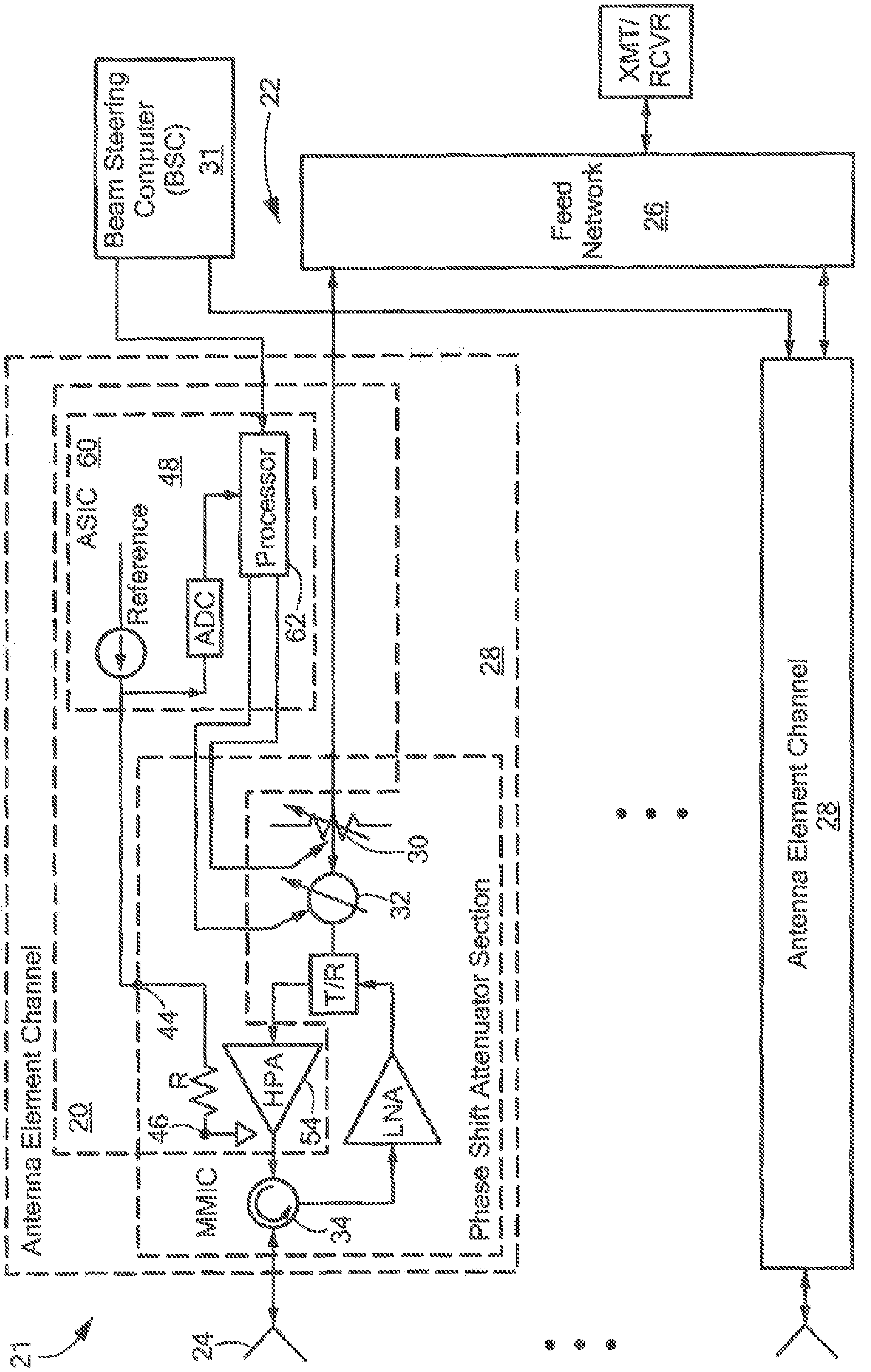

Beam Steering Computer (BSC) 31
22
XMT/ RCVR
Feed Network 26
Antenna Element Channel 20
ASIC 60
48
Reference
ADC
Processor
62
28
MMIC
R
46
44
HPA
54
LNA
T/R
32
30
34
Phase Shift Attenuator Section
21
24
Antenna Element Channel 28

FIG. 3

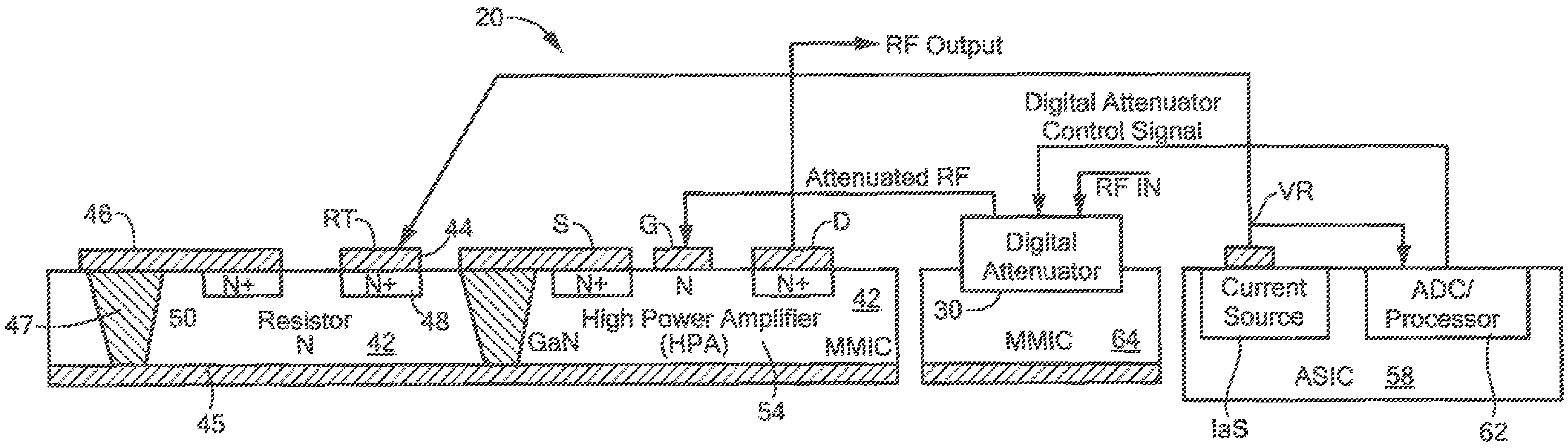

20
RF Output
Digital Attenuator
Control Signal
Attenuated RF
RF IN
VR
46
RT
44
S
G
D
N+
N+
N+
N
N+
47
50
Resistor
N
42
48
GaN
High Power Amplifier
(HPA)
42
MMIC
45
54
Digital
Attenuator
30
MMIC
64
Current
Source
ADC/
Processor
ASIC
58
IaS
62

FIG. 4

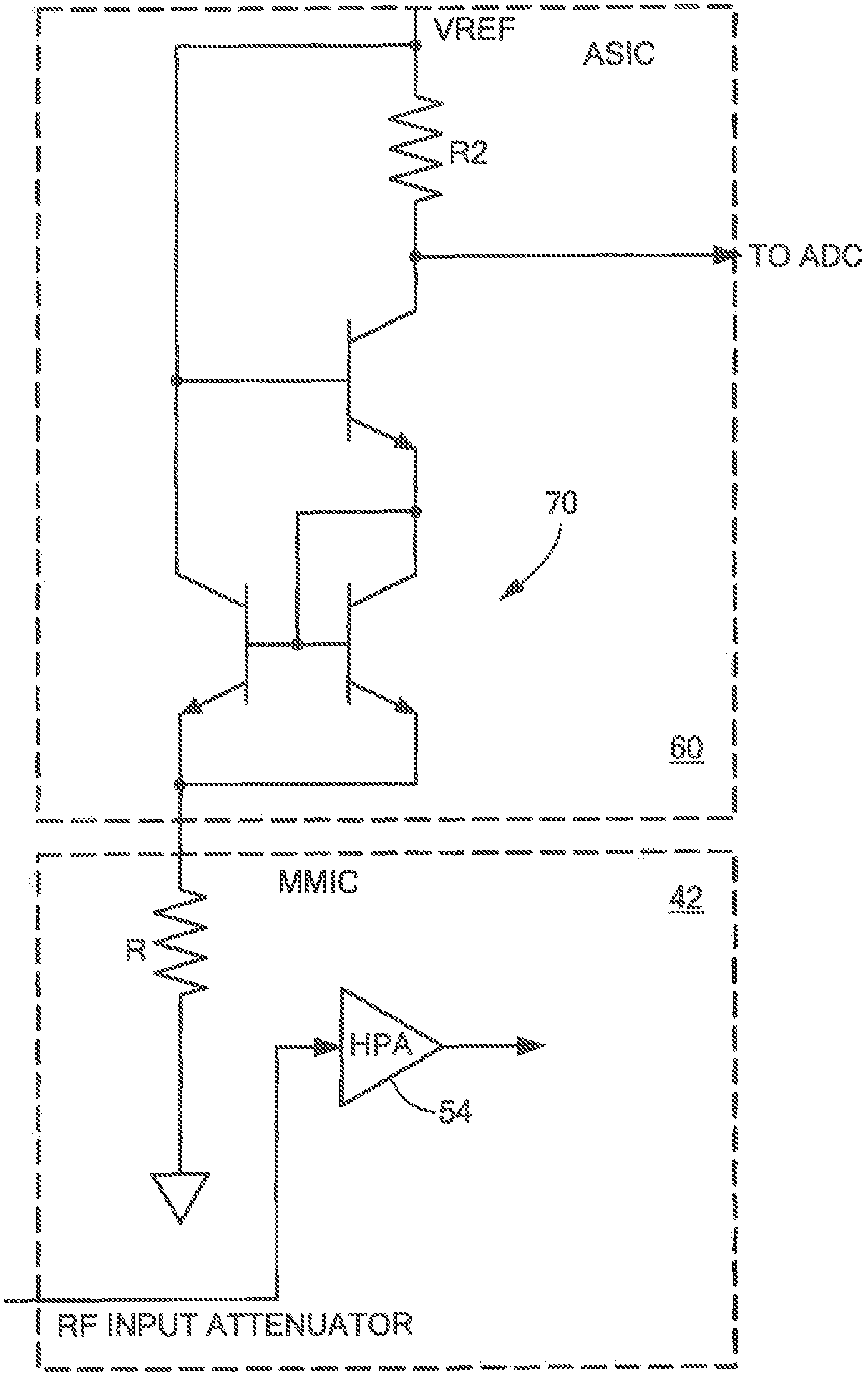


FIG. 5

INTEGRATED CIRCUIT CHIP TEMPERATURE SENSOR

TECHNICAL FIELD

This disclosure relates generally to temperatures sensors and more particularly to integrated circuit chip temperature sensors.

BACKGROUND

As is known in the art, resistors have been used for temperature sensing because their resistance value can change with temperature depending on their resistive material. As is also known, Monolithic Microwave Integrated Circuits ((MMICS) high power amplifiers (HPAs), particularly those fabricated on Gallium-Nitride semiconductor technology, have the ability to generate very large power densities. These large power densities can create thermal management problems at the system level when the amplifier is placed in a packaged environment. Having the ability to accurately sense the temperature of the HPA at the MMIC level and near the source of the heat (i.e. the transistor) is critical to managing the thermal impact of the HPA on the system performance.

SUMMARY

In accordance with the present disclosure, a temperature control system is provided having: a resistor formed in a region of a semiconductor, such resistor having a pair of spaced electrodes in ohmic contact with the semiconductor; at least one device formed in another region of the semiconductor thermally proximate the resistor formed region, such device generating heat in the semiconductor; and circuitry, including a reference connected to one of the pair of electrodes, for operating the resistor in saturation and for sensing variation in the resistor in response to the heat generated by the device and for controlling the heat generated by the device in the semiconductor in response to the sensed variation.

The inventors have recognized that when a semiconductor resistor is biased into saturation, the temperature coefficient of the resistor increases significantly compared with a semiconductor resistor biased in the linear region and therefore when the resistor is biased into saturation it provides greater sensitivity when used as a temperature sensor.

In one embodiment, the region between the pair of electrodes is doped semiconductor.

In one embodiment, the reference is a reference voltage and wherein the circuitry senses variations in current through the resistor in response to variations in the temperature of the semiconductor.

In one embodiment, the reference is a reference current and wherein the circuitry senses variations in voltage said other electrode in response to variations in the temperature of the semiconductor.

In one embodiment the device is a transistor amplifier.

In one embodiment, the resistor and device are formed on a semiconductor and wherein the circuitry is formed on a different semiconductor.

The details of one or more embodiments of the disclosure are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the disclosure will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

FIG. **1** is a schematic diagram of temperature sensing circuit according to the disclosure;

FIG. **2** is a set of curves showing the relationship output voltages of the circuit of FIG. **1** as a function of the temperature of such circuit for various levels of current passing from a constant current source of such circuit through a semiconductor resistor of such circuit both when the resistor is operating in saturation and non-saturation;

FIG. **3** is a simplified block diagram of a phased array radar system including a temperature control system according to the disclosure, such temperature control system including the circuit of FIG. **1**;

FIG. **4** is a simplified cross sectional Sketch of semiconductor chips forming an exemplary one of a plurality of variable phase shifter-variable gain channels used in the phased array radar system of FIG. **4**, such variable phase shifter-variable gain channels having the temperature control system of FIG. **3**; and

FIG. **5** is a simplified schematic diagram of an alternative embodiment of the temperature control system according to the disclosure.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

Referring now to FIG. **1**, a semiconductor resistor, R, (i.e., a resistor having a pair of electrodes **44**, **46** in ohmic contact with a semiconductor **16**) is shown fed from a constant current source Ics. FIG. **2** shows voltage across the pair of electrodes **44**, **46** as a function of the temperature of the resistor, R, for various currents Ics fed to the resistor. It is noted that the variations in output voltage (i.e., the variations in the voltage at electrode **12**) with variations in the temperature of the resistor R increases as the resistor R is operated in increasing saturated regions; i.e., higher values of Ics. It is also noted that as the resistor saturates (i.e., operates with higher values of Ics) the temperature sensitivity (i.e., variation in output voltage as a function of temperature) improves (i.e., increases).

Referring now to FIGS. **3** and **4**, a temperature control system **20** is shown. Here, in this example, the temperature control system **20** is used to control the temperature of a high power amplifier (HPA) in a transmit/receive, phase shifter/attenuator channel of phased array system **21**; it should be understood however that the temperature control system **20** may be used in many other applications.

Thus, here beam forming apparatus **22** (FIG. **3**) is used to form beams of electromagnetic radiation. The shape of the beam is related to the phase and amplitude distributions provided to signals received or transmitted across an aperture; i.e., across antenna elements **24**) of the apparatus **22**. For example, in a phased array antenna, the aperture includes a plurality of antenna elements **24**. Each one of the antenna elements **24** is coupled to a feed network or structure **26** through a corresponding one of a plurality of variable phase shifter-variable gain channels **28**, The feed structure **26** may be a corporate feed or may be through illuminations as in a space fed phased array system. In any event, the channels are controlled by signals from a beam steering computer **31** to provide a collimated and directed beam of radiation. For example, for a broadside (i.e., boresight) beam the phase shift of the signals emanating from each antenna element **24** is zero relative to some arbitrary reference. If the phase shift from element **24** to element **24** differs by a fixed amount from zero, the direction of the main radiation lobe is shifted from broadside accordingly.

Each channel **28** includes: a digitally controlled attenuator **30**; a digitally controlled phase shifter **32**; a transmit/receive switch (T/R); a high power amplifier (HPA); a circulator **34** and a low noise amplifier LNA, arranged as shown. During transmit, RF energy from the transmitter section of transmit/receive section XMT/RCVR, is fed to the plurality of antenna elements **24** through the feed network **26**, the digitally controlled attenuator **30**, the digitally controlled phase shifter **32**, the transmit/receive switch (T/R), the high power amplifier (HPA), and the circulator **34**, as indicated. On receive, energy received by the antenna elements **24** is fed to the receiver section of the XMT/RCVR through the circulator **34**, low noise amplifier LNA, T/R switch, phase shifter **32**, attenuator **30**, and feed network **26**, as indicated.

Here, each channel **28** includes the temperature control system **20**. More particularly, the temperature control system **20** includes: a resistor, R, formed in a region of a semiconductor **42** (FIG. **4**), here, for example, a III-V semiconductor such as, for example, gallium nitride (GaN). The resistor, R, has a pair of spaced electrode **44**, **46** in ohmic contact with doped regions **48**, **50**, respectively here for example N+ doped regions of here, for example, N doped semiconductor **42**. Here, in this example, electrode **44** is connected to a constant current source Ics and electrode **46** is connected to ground **45** through a via **47**.

Also formed in the semiconductor **42**, in close proximate to the resistor R, is at least one device **54**; here for example, a GAN transistor used for the HPA. The temperature control system **20** also includes circuitry **56**, here, for example, formed on another semiconductor **58** (FIG. **3**) as part of an ASIC **60**. Here, for example, the semiconductor **58** is silicon. The circuitry **20** includes a reference, here the constant current source Ics, connected to one of the pair of electrodes, here electrode **44**, for operating the resistor R in saturation and for sensing variation in the voltage at electrode **44** in response to the heat generated by the device **54** and for controlling the heat generated by the device **54** in the semiconductor **42** in response to the sensed voltage variation at electrode **44**.

Here, the voltage at electrode **44** is fed to the ASIC **60** where it is converted into a corresponding digital signal by an analog to digital converter (ADC). The digital signal is fed to a processor **62** of the ASIC **60**. In one implementation, for example, the processor **62** has stored therein, as for example in a Read Only Memory (ROM), not shown, the relationship between the voltage and temperature from the data in FIG. **2**. A predetermined reference or desired temperature for the semiconductor **42** is also stored in the ROM. The processor **62** produces a temperature adjusting control signal representative of the difference between the actual temperature of the semiconductor and the desired temperature. The processor **62** also produces beam steering control signal from the beam steering computer **31**. The processor **62** modifies the beam steering control signal by the temperature adjusting control signal to produce a combined control signal for the phase shifter **32** and the variable, digitally controlled attenuator **30**. The phase shifter **32** and the variable, digitally controlled attenuator **30** are here formed, in this example, on a third semiconductor **64**, here also a III-V semiconductor. This third semiconductor **64** has fed to it a radio frequency (RF) signal to be amplified by the HPA after passing through the digitally controlled attenuator **30**. Thus here, in this example, the level of the RF input to the HPA is varied in accordance with variations in the temperature sensed by the resistor R. More particularly, in the example, as the temperature proximate the HPA increase, such increase in temperature is sensed by the resistor R and the voltage increase at electrode **44** is fed to the processor **62** resulting in the processor **62** sending as the combined control signal to attenuator **60** to increase the attenuation a small amount in addition to the attenuation required by the beam steering computer **31** and thereby reduce the RF input to the HPA. This reduced RF input result in a corresponding reduction in the heat generated temperature generated by the HPA. The effect then is to provide a feedback, temperature control system. It should be understood that this is an example of the operation of the processor **62** in modifying the beam steering control signal. Other implementations may be used. For example, the output of the ADC may be directly compared with a stored digital word representative of the desired temperature of the semiconductor **42** without storing in the ROM the data from the curve in FIG. **2**.

A number of embodiments of the disclosure have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the disclosure. For example, the resistor R on the semiconductor **42** may be fed with a reference voltage on the ASIC **60**, as shown in FIG. **5**. The ASIC **60** includes a current mirror **70** such as a Wilson current mirror, here formed by bipolar transistors but FETs may be used. The current mirror **70** produces a voltage across a resistor R**2** on the ASIC **60** proportional to the current through the resistor R on the semiconductor **42**. Thus, variations in the semiconductor caused by heating of the HPA are sensed by the resistor R, as described above, and such variations cause a corresponding change in the current through the resistor R. The current through resistor R is mirrored by the current mirror into corresponding changes in the current through resistor R**2** and hence produce corresponding changes in the voltage across the resistor R**2**. The voltage across R**2** is converted into digital signals by the ADC for the processor **62** as described above. Thus, current changes through the resistor R produce corresponding changes through R**2** and hence in the voltage produced by the ADC. Accordingly, other embodiments are within the scope of the following claims.

What is claimed is:

1. A temperature control system, comprising:

a semiconductor;

a resistor formed in a region of the semiconductor, such resistor having a pair of spaced electrodes in ohmic contact with the semiconductor;

at least one device formed in another region of the semiconductor thermally proximate the resistor formed region, such device generating heat in the semiconductor;

circuitry, including a reference connected to one of the pair of electrodes, for operating the resistor in saturation and for sensing variation in the resistor in response to the heat generated by the device and for controlling the heat generated by the device in the semiconductor in response to the sensed variation.

2. The temperature control circuitry recited in claim **1** wherein the region between the pair of electrodes is doped semiconductor.

3. The temperature control circuitry recited in claim **1** wherein the reference is a reference voltage and wherein the circuitry senses variations in current through the resistor in response to variations in the temperature of the semiconductor.

4. The temperature control circuitry recited in claim **1** wherein the reference is a reference current and wherein the circuitry senses variations in voltage at said one of the electrodes in response to variations in the temperature of the semiconductor.

5. The temperature control circuitry recited in claim **1** wherein the device is a transistor amplifier.

6. The temperature control circuitry recited in claim **3** wherein the region between the pair of electrodes is doped semiconductor.

7. The temperature control circuitry recited in claim **4** wherein the region between the pair of electrodes is doped semiconductor.

8. The temperature control circuitry recited in claim **5** wherein the region between the pair of electrodes is doped semiconductor.

9. A temperature control system, comprising:

a semiconductor;

a resistor formed in a region of the semiconductor, such resistor having a pair of spaced electrodes in ohmic contact with the semiconductor;

a transistor formed in another region of the semiconductor thermally proximate the resistor formed region, such transistor generating heat in the semiconductor;

circuitry coupled to the pair of electrodes, for operating the resistor in saturation and for sensing variation in current through, or voltage between, the pair of spaced electrodes of the saturation operated resistor and for controlling the temperature of the semiconductor in response to the sensed variation.

10. The temperature control circuitry recited in claim **3** wherein **1** the region between the pair of electrodes is doped semiconductor.

11. The temperature control circuitry recited in claim **9** wherein the reference is a reference voltage and wherein the circuitry senses variations in current through the resistor in response to variations in the temperature of the semiconductor.

12. The temperature control circuitry recited in claim **9** wherein the reference is a reference current and wherein the circuitry senses variations in voltage at one of the electrodes in response to variations in the temperature of the semiconductor.

13. The temperature control circuitry recited in claim **9** wherein the transistor is arranged as an amplifier.

14. The temperature control circuitry recited in claim **11** wherein the region between the pair of electrodes is doped semiconductor.

15. The temperature control circuitry recited in claim **12** wherein the region between the pair of electrodes is doped semiconductor.

16. The temperature control circuitry recited in claim **13** wherein the region between the pair of electrodes is doped semiconductor.

17. The temperature control circuitry recited in claim **1** wherein the resistor and device are formed on a III-V semiconductor and wherein the circuitry is formed on a different semiconductor.

18. The temperature control circuitry recited in claim **9** wherein the resistor and transistor are formed on a III-V semiconductor and wherein the circuitry is formed on a different semiconductor.

19. The temperature control circuitry recited in claim **17** wherein the region between the pair of electrodes is doped semiconductor.

20. The temperature control circuitry recited in claim **18** wherein the region between the pair of electrodes is doped semiconductor.

* * * * *